Article

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Hanzlíková, I, Richards, James, Hébert-Losier, K and Smékal, D

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The effect of proprioceptive knee bracing on knee stability after anterior cruciate ligament reconstruction

I Hanzlíková[1,3], J Richards[2], K Hébert-Losier[3], D Smékal[1]

[1] Faculty of Physical Culture, Palacký University, Olomouc, Czech Republic

[2] Allied Health Research Unit, University of Central Lancashire, United Kingdom

[3] Faculty of Health, Sport and Human Performance, Adams Centre for High Performance, The University of Waikato, New Zealand

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Corresponding author:

Ivana Hanzlíková - email: xhanzlikova@gmail.com

Highlights

- Bracing increased sagittal plane angular velocity for single leg drop jump
- Bracing reduced transverse plane motions for pivot turn jump
- Participants reported that two tasks were easier to perform with the brace
- These effects are clinically relevant in the management of ACL injured patients

Abstract

Background: Injury to the anterior cruciate ligament (ACL) is common among young athletes and can impact knee stability and control. Wearing proprioceptive knee braces can improve knee control and may reduce the risk factors associated with injury and re-injury, although the effect of such braces after ACL reconstruction (ACLR) is unclear.

Research question: This study aimed to determine the effect of proprioceptive knee bracing on knee control and subjective rating of participants post ACLR during three dynamic tasks.

Methods: Fifteen participants 2 – 10 years post ACLR performed a slow step down, single leg drop jump, and pivot turn jump with and without a proprioceptive knee brace. Knee kinematics in the sagittal (flexion – extension), coronal (abduction – adduction), and transverse (internal – external rotation) planes were collected using a 3D infrared system. Paired *t*-tests were performed to explore differences in knee angles and angular velocities between the no brace and brace conditions during the three tasks. After each task, subjective ratings regarding ease of the task were recorded.

Results: The brace reduced the peak knee external rotation angle and range of motion in the transverse plane during the pivot turn jump task, and significantly increased the maximum knee flexion angular velocity during the single leg drop jump task. The majority of participants reported that tasks were easier to perform with the proprioceptive brace than without.

Significance: This study confirms that proprioceptive knee braces can significantly influence knee kinematics during dynamic tasks post ACLR. The observed effects were clinically relevant.

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Introduction

The anterior cruciate ligament (ACL) plays an important role in the stability of the knee. Injury to the ACL is common with a reported incidence of 68.6 per 100,000 people, with approximately 70% of acute ACL injuries occuring among young athletes [1]. The majority of acute ACL injuries are surgically reconstructed to manage instability of the knee, with athletes usually aiming to return to sport as fast as possible. However, anterior cruciate ligament reconstruction (ACLR) does not completely restore knee function [2]. Studies have shown that only 45% of patients return to the same or higher level of activity 2 years after an unilateral ACLR, with a considerable percentage of patients still reporting moderate to severe disability during walking (31%) and activities of daily living (44%) [3,4].

The ACL contains a variety of sensory nerve endings that play an important role in knee proprioception [5]. These nerve endings are also affected when the ACL ruptures, which results in deficits in knee proprioception detectable not only in the ACLR knee, but also in their contralateral knee [6]. Previous studies have shown that patient's proprioceptive ability relate to their subjective ratings of knee function [7].

Braces are frequently used in the treatment of knee problems to reduce pain, improve knee joint control, and reduce the risk of injury or re-injury. The use of soft knee braces has been shown to improve proprioception [8,9], which has been identified as an important mechanism in managing knee instability and ACL injury [10].

The reported benefits of knee bracing may result from mechanical support of the joint and improved proprioception. Both mechanisms more readily apply to functional braces with solid components, however elastic knee sleeves offer no mechanical support as the forces in the knee joint are many times greater than the resistance of such interventions [11]. The stabilising effect of elastic braces may partially be explained by the reaction of slowly adapting

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mechanoreceptors to the stretch applied to the skin surrounding the knee joint [12]. With the skin contact from bracing activating sensory receptors and providing more afferent information to the brain through cutaneous sensory stimulation and thereby improving the neuromuscular control of the knee joint [12]. This assumption was confirmed by Thijs et al. [13] who captured functional magnetic resonance images during knee movements with and without a soft brace deprived of mechanical hinges. Significantly higher activation of the primary sensorimotor cortex and left superior parietal lobule of the brain was observed during knee movement with the soft brace. Increases in afferent information influences the brain centres responsible for movement program generation and may improve motor control of the knee joint. Thijs et al. [13] found greater brain activation during knee movements when wearing the knee brace than knee sleeve which supports the clinical studies in the area that also report greater effect of knee sleeves than taping techniques [11,14–16].

The Reaction Web Knee Brace (DJO, Inc.) is a distinct alternative to the basic knee sleeve and incorporates an elastometric web design (Fig. 1). Khadavi et al. [17] showed that the Reaction Web Knee Brace reduces knee pain, increases function, and enhances quality of life in individuals with patellofemoral pain. Hanzlíková et al. [18] previously determined that this type of bracing changes knee control in healthy individuals during a slow step down movement and two more dynamic sport-related tasks. The aim of this current study was to explore if the Reaction Web Knee Brace can offer important changes in knee control in participants after ACLR during dynamic tasks, and whether these influence subjective ratings. It was hypothesised that the brace would influence knee kinematics. More specifically, we hypothesised that the brace would reduce the transverse and coronal plane motion and angular velocity values during the pivot turn jump task.

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Methods

Sample size requirements were calculated from standard two-tailed hypothesis equations using an 80% power (β = 0.20), 5% significance level (α = 0.05), critical values of the *t* distribution, and data from a previous study [18]. For sample size estimation, two variables which were previously linked with ACL injury were investigated, knee valgus angle and knee internal rotation angle. These equations indicated that eight participants were needed to identify differences between no brace and brace conditions.

Eighty-seven potential participants who had previously undergone an ACLR and post-surgery rehabilitation were identified from the database of a rehabilitation centre and contacted by phone or email. Fifteen (10 males and 5 females) agreed to participate in this study. Age, height, mass, and body mass index (mean ± standard deviation) characteristics for males were 34.2 ± 5.8 years, 181.7 ± 9.3 cm, 85.1 ± 12.2 kg, and 25.9 ± 2.5 kg/m^2; and for females were 31.2 ± 8.4 years, 167.6 ± 3.0 cm, 65.6 ± 4.2 kg, and 23.4 ± 1.3 kg/m^2. Eight participants had undergone ACLR on their dominant side (i.e., leg used to kick a ball) and seven on their non-dominant side. Eight participants had received an autograft from the middle part of the patellae ligament, five an autograft from the semitendinosus-gracilis tendon, and two an allograft harvested from cadavers.

It has been reported that ligament remodelling occurs mostly during the first two years of graft implantation [19,20], with osteoarthritis seen on average 10 years post reconstruction [21]. Therefore, all participants included in this study were between 2 – 10 years (mean 6.5 years) post ACLR. However, the radiographic or symptomatic osteoarthritis status of the participants were not examined in this study.

All participants fulfilled the inclusion criteria of: age between 20 to 50 years, no injuries of other ligaments of the knee, no current musculoskeletal injuries or disorders, no history of

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additional surgery or traumatic injury to the lower extremities or lower back, and no history of medical conditions that could limit physical activity participation. Furthermore, participants had to be 2 – 10 years post ACLR. All data collection conformed to the Declaration of Helsinki and volunteers gave written informed consent prior to participation.

Each participant performed five repetitions of three different tasks (slow step down, single leg drop jump, and pivot turn jump) under two conditions (no brace and Reaction Web Knee Brace). The testing order of the two conditions was randomised in a first instance, with the testing order of the tasks randomised in a second instance. The order of testing of the three tasks was kept consistent between conditions for a given participant.

All participants completed the whole protocol in a single testing session wearing their own sport footwear, with the exception of one participant who did not perform the single leg drop jump due to kinesiophobia. Practice attempts were allowed for each task (typically two attempts) until participants indicated that they felt ready to proceed with testing. For the slow step down task, participants were asked to step down as slowly as possible from a 20 cm step, touching down with the heel of the contralateral limb. For the single leg drop jump, participants were asked to begin standing unilaterally on their ACLR leg on top of the 20 cm step, then to drop off the box landing on the same foot. For the pivot turn jump, participants were asked to hop forwards approximately 60 cm from their contralateral leg, land on their ACLR leg, and immediately pivot 180° with an internal rotation to hop back to their starting location onto their contralateral leg in one movement. After each task once both brace and no brace conditions were completed, participants evaluated whether the task was easier with or without the brace using the following 5-point Likert-type scale: 1 - more difficult with brace, 2 - slightly more difficult with brace, 3 - same with or without brace, 4 - slightly easier with brace, 5 - easier with brace. This scale was developed specifically for this study to capture perception of ease and stability from the participants, but has not been explicitly validated.

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Kinematic data were collected using a six camera infrared Motion Capture System (Vicon Industries Inc., New York, USA) sampling at 100 Hz. Reflective markers were placed on the foot, shank, and thigh using the Calibrated Anatomical System Technique [22]. The thigh and shank marker clusters were placed above and below the brace, respectively (Fig. 1). Raw kinematic data were exported to Visual3D (C-Motion Inc., USA). Kinematic data were filtered using a fourth-order Butterworth filter with a cut off frequency of 15 Hz. Knee joint kinematics were calculated relative to the shank coordinate system. The kinematics were calculated using an XYZ cardan sequence, equivalent to the joint coordinate system proposed by Grood and Suntay [23]. The kinematic data about the knee were quantified between initial contact and maximum knee flexion to target the eccentric loading phase during single limb support. The maximal values, minimal values, and range of angles and angular velocities of the knee in the sagittal (flexion – extension), coronal (abduction – adduction), and transverse (internal – external rotation) planes were extracted. In addition, kinematic data for the knee at initial contact for the single leg drop jump and pivot turn jump were also extracted. The overall reduction in range of motion in the coronal or transverse planes suggest better knee join stability [24,25]; however, range of motion alone does not necessarily inform us about the control of these movements. For this reason, knee angular velocities were also assessed in accordance with previous studies [18,26] to provide further insights on the dynamic control and stability of the knee joint.

Paired *t*-tests were performed to investigate any kinematic differences between the braced and no braced conditions during the three tasks. Measures of effect size, Hedges' g (g) were calculated for significant results from the paired *t*-tests. Thresholds for interpreting the magnitude of Hedges 'g were: $0.20 \leq g < 0.50$ for small effects, $0.50 \leq g < 0.80$ for medium effects, and $g \geq 0.8$ for large effects [27]. Paired *t*-tests were used to compare the position of the knee at initial contact for the two more dynamic tasks. The statistical significance level was set

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at $\alpha \leq 0.05$ for all analyses, with differences between conditions expressed using mean differences and 95% confidence intervals [95% CI]. Participants' answers from the Likert-type scale were described using counts, as well as median and mode as central tendency indicators. Wilcoxon signed rank test with exact *p* values were calculated to identify whether participants' self-reported scores significantly differed from the mid-point score of 3 (i.e., same with or without the brace).

Fig. 1. Reaction Web Knee Brace and reflective markers placed on the foot, shank, and thigh using the Calibrated Anatomical System Technique.

Results

Mean and standard deviation values for the kinematic parameters investigated are presented in Table 1 for each condition and task, along with the *p*-values from the *t*-tests.

Differences between conditions

The brace had no effect on the coronal plane kinematics; however, significant differences between the brace and no brace conditions were seen in the transverse and sagittal planes. More specifically, the brace significantly reduced external rotation by 1.7° ($p = 0.042$) and transverse

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plane range of motion by 2.4° (p = 0.004) during the pivot turn jump. The brace increased knee flexion angular velocity by 40.5 °/s (p = 0.029) during the single leg drop jump. However, all significant results from the paired *t*-tests indicated a small effect size according to the Hedges' *g* test, Table 2.

Perception

Participants reported that the slow step down and pivot turn jump tasks were slightly easier to perform with the proprioceptive brace than without, with the median and mode of scores being 4 on the 5-point Likert-type scale. The pivot turn jump task scores were significantly higher than the mid-point score of 3 (same with or without the brace, p = 0.007). Participants reported that the difficulty of the single leg drop jump was the same with or without brace, with median and mode scores of 3. The frequency of the answers are shown in Figure 2 for every task.

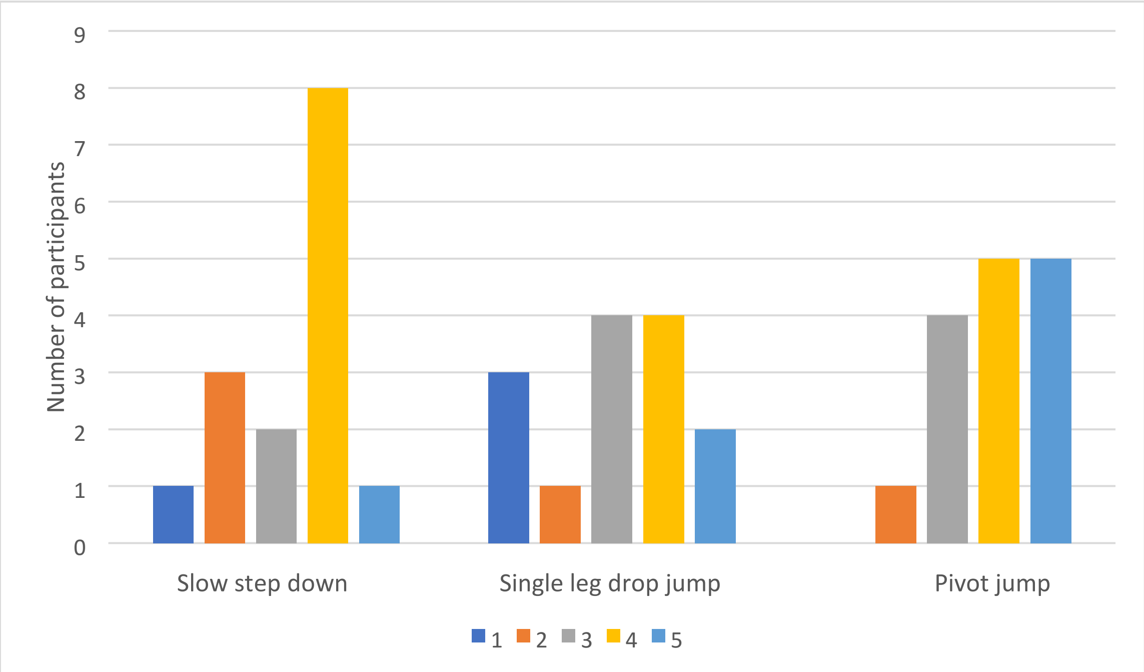

Figure 2. Subjective ratings regarding ease of the task. 1- more difficult with brace, 2- slightly more difficult with brace, 3- same with or without brace, 4- slightly easier with brace, 5- easier with brace.

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Table 1 Mean (standard deviation) values for the knee kinematic parameters in ACLR participants (*n* = 15) for each condition and task with paired t-test p-values comparing Brace vs No Brace conditions.

		Knee angle (degrees)			Knee angular velocity (degrees/s)		
		SD	DJ	PJ	SD	DJ	PJ
Extension	**NB**	22.2 (5.8)	18.0 (2.7)	14.0 (4.2)	7.7 (16.6)	-9.1 (36.0)	-274.0 (73.2)
	B	22.6 (6.2)	17.2 (3.6)	13.6 (3.6)	-0.5 (19.2)	-9.2 (44.0)	-281.1 (59.6)
Paired t-test p-value		0.700	0.240	0.740	0.151	0.992	0.359
Flexion	**NB**	81.4 (8.9)	51.72 (6.49)	52.2 (9.0)	60.1 (20.8)	478.0 (181.0)	293.6 (90.2)
	B	82.8 (8.2)	51.8 (7.4)	51.4 (8.2)	55.6 (20.6)	518.5 (197.1)	302.3 (99.7)
Paired t-test p-value		0.118	0.877	0.203	0.260	**0.029**	0.416
Range of motion	**NB**	59.2 (8.2)	33.7 (7.0)	38.3 (10.7)	52.42 (24.2)	487.1 (197.9)	567.6 (114.1)
	B	60.2 (8.7)	34.6 (8.0)	37.8 (9.0)	56.2 (33.4)	527.7 (221.3)	583.5 (139.1)
Paired t-test p-value		0.459	0.255	0.534	0.623	0.076	0.332
Valgus	**NB**	-1.9 (4.8)	-2.7 (5.4)	-3.7 (6.0)	-26.7 (25.0)	-114.5 (67.8)	-83.4 (44.7)
	B	-1.3 (4.4)	-2.2 (4.4)	-3.7 (5.0)	-27.0 (37.3)	-115.2 (87.3)	-80.2 (37.7)
Paired t-test p-value		0.073	0.395	0.894	0.969	0.962	0.726
Varus	**NB**	3.8 (5.7)	4.4 (4.0)	7.4 (4.4)	33.4 (33.1)	136.5 (114.8)	80.5 (36.5)
	B	4.0 (5.2)	4.1 (3.7)	7.1 (4.2)	30.8 (36.6)	111.3 (88.0)	97.2 (59.7)
Paired t-test p-value		0.691	0.455	0.597	0.815	0.180	0.286
Range of motion	**NB**	5.7 (4.2)	7.1 (2.8)	11.1 (3.9)	60.1 (47.3)	251.0 (157.5)	163.9 (73.0)
	B	5.3 (3.5)	6.3 (3.1)	10.7 (3.4)	57.8 (72.7)	226.5 (159.0)	177.5 (91.5)
Paired t-test p-value		0.175	0.177	0.525	0.885	0.216	0.547
External rotation	**NB**	-4.8 (6.4)	-7.7 (7.2)	-14.6 (7.7)	-23.7 (18.3)	-198.3 (124.9)	-191.2 (112.9)
	B	-4.8 (6.0)	-7.5 (6.0)	-12.9 (7.0)	-23.7 (17.6)	-181.0 (147.4)	-201.9 (139.8)
Paired t-test p-value		0.990	0.718	**0.042**	0.998	0.483	0.719
Internal rotation	**NB**	1.0 (5.8)	2.7 (7.3)	5.8 (7.4)	19.6 (15.2)	154.5 (117.6)	191.1 (76.0)
	B	1.0 (6.4)	1.3 (6.3)	5.0 (7.6)	17.4 (9.4)	172.5 (143.1)	191.7 (89.0)
Paired t-test p-value		0.986	0.106	0.051	0.581	0.348	0.983
Range of motion	**NB**	5.8 (2.2)	10.3 (4.9)	20.4 (9.4)	43.3 (29.1)	352.8 (137.5)	382.33 (153.1)
	B	5.7 (3.4)	8.7 (3.3)	18.0 (7.8)	41.2 (24.8)	353.5 (214.5)	393.5 (221.0)
Paired t-test p-value		0.982	0.091	**0.004**	0.822	0.986	0.824

SD – slow step down, DJ – single leg drop jump, PJ – pivot turn jump, NB – no brace, B – brace.

Table 2 Mean difference [95% confidence interval], Hedge's *g*, and *p*-values between conditions (no brace – brace) in the knee kinematic parameters of ACLR participants (*n* = 15) from significant paired *t*-test results.

	Mean difference [95% CI]	Hedge's *g*	*p*-value
Pivot turn jump			
Maximum external rotation angle	- 1.7 [- 3.3, - 0.07]	0.231	0.042
Range of motion in transverse plane	2.4 [0.89, 3.99]	0.278	0.004
Single leg drop jump			
Peak flexion angular velocity	- 40.5 [- 76.27, - 4.72]	0.214	0.029

Discussion

This study examined 3D kinematics of the knee during three different tasks in ACLR participants with and without a proprioceptive knee brace. The brace did not significantly

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influence knee kinematics during the slow step down. This result is contrary to the findings on healthy individuals [18], which showed a significant decrease in the range of angular velocity values in the transverse plane during slow step down. Selfe et al. [14] used the slow step down task to test the effect of taping and a patellofemoral brace and found that both interventions significantly decrease knee valgus and range of motion in the transverse plane in healthy individuals. Selfe et al. [11] repeated the same protocol in individuals with patellofemoral pain. Both brace and tape decreased the range of motion of the knee in the coronal and transverse planes. In addition, Hanzlíková et al. [18], showed the brace significantly decreased valgus and varus motion of the knee during the single leg drop jump in healthy individuals, but this effect was not seen in ACL reconstructed participants. However, a significant increase in maximal knee flexion angular velocity was seen with the brace during the single leg drop jump in ACL reconstructed participants. These differences could be explained by differing movement strategy among healthy individuals and participants after ACLR, which may result in a different effect of the brace.

In the transverse plane the brace significantly reduced external rotation and range of motion and almost significantly ($p = 0.051$) reduced internal rotation during the pivot turn jump task. When compared with the previous data on healthy participants [18], the brace significantly reduced valgus, internal rotation, and range of motion in the coronal and transverse planes during the pivot turn jump task. For both groups the brace significantly changed the position of the knee toward a more neutral position. It is interesting that these changes were seen in the pivot turn jump, which was the most demanding task, and showed the greatest range of motion in the transverse plane. This motion is often associated with ACL injury mechanisms, therefore the brace may be providing a change in movement which may help to prevent ACL re-injury. This effect of prophylactic knee bracing is supported by Sinclair et al. [28] who studied similar

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movements on 20 female netball players, and showed that proprioceptive bracing can significantly reduce the range of motion in the transverse plane.

Even though the changes in the knee joint angles between the brace and no brace conditions appear small (i.e., a 1.7° reduction of external rotation angle and 2.4° reduction in the range of motion in the transverse plane during the pivot turn jump), there is a need to consider the range of motion values during the task. When the effects of the brace are expressed as a percentage of the range of motion values for the pivot turn jump, the brace reduced motion in the transverse plane by 10%. In addition, studies which have compared ACL reconstructed knees with contralateral knees kinematics found that the mean difference in range of motion values in the transverse plane ranged between 1.9 to 3.8° during running [29–31] and between 1.3° to 3.0° during walking [32]. During cutting, the mean difference between ACL deficient knees and ACL intact knees has been reported to range between 1.0° to 3.3° in the transverse plane when cutting to 30° and between 0.1° to 1.0° when cutting to 45° [31]. Based on this evidence, we can say that the difference between no brace and brace conditions in the transverse plane for pivot turn jump is clinically relevant.

The brace in the current study increased the peak flexion angular velocities in the sagittal plane by 40.5 °/s (~8%) during single leg drop jump, which might reflect greater confidence in participants' ability to perform dynamic tasks and ability to cope with task demands. Indeed, some patients with ACL injury are able to return to the same activity level as before their injury (copers), while others are not (non-copers). Alkjær et al. [33] tested the difference in the sagittal plane knee joint kinematics between copers, non-copers, and healthy controls during the forward lunge task. These authors found that knee flexion angular velocity was 221.5 °/s for non-copers, 256.1 °/s for copers, and 311.3 °/s for healthy controls. This result suggests that the effect of the brace on flexion angular velocity and range of angular velocity in the sagittal plane seen in this current study is clinically relevant.

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Participants subjectively felt that the pivot turn and slow step down tasks were easier with the brace, which is in agreement with Hart et al. [34] who explored perceived stability during the slow step down task. This notion is supported by Harput et al. [35], who showed that wearing a brace can decrease kinesiophobia, and therefore yield an increase in performance.

The brace was most effective in influencing transverse plane motion, which suggests it could be useful for patients with rotational instability of the knee. Two of the tasks used were sportspecific, indicating that the use of such braces could help in returning to sport following ACL injury, and could reduce the risk factors associated with reinjury. Currently most of the research concentrates on the sagittal plane only; however, coronal and transverse plane kinematics are more related to ACL injury mechanisms. Therefore, further methodologically-strong quality studies are needed to compare kinematics in all planes between no brace and brace conditions to explore whether the soft brace has the same effect for ACL deficient patients, ACL reconstructed patients, and in copers than non-copers.

One of the limitations of this study was that the sample size was not high enough to allow us to compare the effect of the brace between males and females or between groups of participants with different graft types (autograft from patellae ligament, autograft from semitendinosusgracilis tendon, and allograft from cadavers). Another limitation is that we did not examine the radiographic or symptomatic osteoarthritis status of participants. Even though the 3D motion capture system is considered to be a gold standard for movement analysis, the markers are placed on the skin and skin movement can influence the results.

Conclusion

The Reaction Web Knee Brace changed the knee joint kinematics in participants between 2-10 years post ACL reconstruction. These significant changes were seen in the sagittal plane during

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the single leg drop jump and transverse plane for the pivot turn jump, which support the notion that such bracing can offer clinically important changes in joint control.

References

[1] T.L. Sanders, H. Maradit Kremers, A.J. Bryan, D.R. Larson, D.L. Dahm, B.A. Levy, M.J. Stuart, A.J. Krych, Incidence of Anterior Cruciate Ligament Tears and Reconstruction, Am. J. Sports Med. 44 (2016) 1502–1507.

[2] E. Ageberg, Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation - Using the anterior cruciate ligament-injured knee as model, J. Electromyogr. Kinesiol. 12 (2002) 205–212.

[3] W.R. Dunn, K.P. Spindler, A. Annunziato, B.R. Wolf, J.T. Andrish, J.A. Bergfeld, M.H. Jones, R.D. Parker, D.C. Flanigan, C.C. Kaeding, R.G. Marx, M.J. Matava, R.W. Wright, E.C. McCarty, M. Wolcott, A. Vidal, F.E. Harrell, R.S. Dittus, Predictors of Activity Level 2 Years after Anterior Cruciate Ligament Reconstruction (ACLR), Am. J. Sports Med. 38 (2010) 2040–2050.

[4] F.R. Noyes, P.A. Mooar, D.S. Matthews, The symptomatic anterior cruicate-deficient knee. I. The long-term functional disability in athetically active individuals, J. Bone Joint Surg. Am. 65 (1983) 154–162.

[5] H. Johansson, P. Sjölander, P. Sojka, A sensory role for the cruciate ligaments., Clin. Orthop. Relat. Res. 268 (1991) 161–178.

[6] D. Roberts, T. Fridén, A. Stomberg, A. Lindstrand, U. Moritz, Bilateral proprioceptive defects in patients with a unilateral anterior cruciate ligament reconstruction: A comparison between patients and healthy individuals, J. Orthop. Res. 18 (2000) 565–571.

[7] D. Roberts, T. Fridén, R. Zätterström, A. Lindstrand, U. Moritz, Proprioception in people with anterior cruciate ligament-deficient knees: comparison of symptomatic and asymptomatic patients., J. Orthop. Sports Phys. Ther. 29 (1999) 587–94.

[8] L. Herrington, C. Simmonds, J. Hatcher, The effect of a neoprene sleeve on knee joint position sense, Res. Sport. Med. 13 (2005) 37–46.

[9] G.K.H. Wu, G.Y.F. Ng, A.F.T. Mak, Effects of Knee Bracing on the Sensorimotor Function of Subjects with Anterior Cruciate Ligament Reconstruction, Am. J. Sports Med. 29 (2001) 641–645.

[10] D. Théoret, M. Lamontagne, Study on three-dimensional kinematics and electromyography of ACL deficient knee participants wearing a functional knee brace during running, Knee Surgery, Sport. Traumatol. Arthrosc. 14 (2006) 555–563.

[11] J. Selfe, D. Thewlis, S. Hill, J. Whitaker, C. Sutton, J. Richards, A clinical study of the biomechanics of step descent using different treatment modalities for patellofemoral pain, Gait Posture. 34 (2011) 92–96.

[12] B.B. Edin, Cutaneous afferents provide information about knee joint movements in humans, J. Physiol. 531 (2001) 289–297.

[13] Y. Thijs, G. Vingerhoets, E. Pattyn, L. Rombaut, E. Witvrouw, Does bracing influence brain activity during knee movement: An fMRI study, Knee Surgery, Sport. Traumatol. Arthrosc. 18 (2010) 1145–1149.

[14] J. Selfe, J. Richards, D. Thewlis, S. Kilmurray, The biomechanics of step descent under different treatment modalities used in patellofemoral pain, Gait Posture. 27 (2008) 258–263.

[15] J. Richards, A. Chohan, J. Janssen, J. Selfe, Taping and bracing of the knee joint: a ladder of conservative intervention for patellofemoral pain, Physiotherapy. 101 (2015) e1280–e1281.

[16] G.J. McCall, S.S. Galen, M.J. Callaghan, G.J. Chapman, A. Liu, R.K. Jones, Effect of patellofemoral brace and tape on knee joint kinematics and kinetics, J. Prosthetics Orthot. 26 (2014) 146–153.

[17] M. J. Khadavi, Y.T. Chen, M. Fredericson, A Novel Knee Orthosis in the Treatment of Patellofemoral Pain Syndrome, Open J. Ther. Rehabil. 03 (2015) 56–61.

[18] I. Hanzlíková, J. Richards, M. Tomsa, A. Chohan, K. May, D. Smékal, J. Selfe, The effect of proprioceptive knee bracing on knee stability during three different sport related movement tasks in healthy subjects and the implications to the management of Anterior Cruciate Ligament (ACL) injuries, Gait Posture. 48 (2016).

[19] S. Scheffler, F. Unterhauser, A. Weiler, Graft remodeling and ligamentization after cruciate ligament reconstruction, Knee Surgery, Sport. Traumatol. Arthrosc. 16 (2008) 834–842.

[20] A. Weiler, R. Peine, A. Pashmineh-Azar, C. Abel, N.P. Südkamp, R.F.G. Hoffmann, Tendon healing in a bone tunnel. Part I: Biomechanical results after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep, Arthroscopy. 18 (2002) 113–123.

[21] B. Luc, P.A. Gribble, B.G. Pietrosimone, Osteoarthritis prevalence following anterior cruciate ligament reconstruction: A systematic review and numbers-needed-to-treat analysis, J. Athl. Train. 49 (2014) 806–819.

[22] A. Cappozzo, F. Catani, U. Della Croce, A. Leardini, Position and orientation in space of bone during movement: anatomival frame definition and determination, Clin. Biomech. 10 (1995) 171–178.

DOI: 10.1016/j.gaitpost.2018.10.026

[23] E.S. Grood, W.J. Suntay, A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee, J. Biomech. Eng. 105 (1983) 136.

[24] J. Selfe, J. Richards, D. Thewlis, S. Kilmurray, The biomechanics of step descent under different treatment modalities used in patellofemoral pain, Gait Posture. 27 (2008) 258–263.

[25] J. Richards, A. Chohan, J. Janssen, J. Selfe, Taping and bracing of the knee joint: a ladder of conservative intervention for patellofemoral pain, Physiotherapy. 101 (2015) e1280–e1281.

[26] K. Budini, J. Richards, T. Cole, D. Levine, R. Trede, L. St. George, J. Selfe, An exploration of the use of Inertial Measurement Units in the assessment of dynamic postural control of the knee and the effect of bracing and taping, Physiother. Pract. Res. (2018) 3–26.

[27] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs., Front. Psychol. 4 (2013) 863.

[28] J.K. Sinclair, H. Vincent, J.D. Richards, Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements, Phys. Ther. Sport. 23 (2017) 93–98.

[29] S. Tashman, D. Collon, K. Anderson, P. Kolowich, W. Anderst, Abnormal Rotational Knee Motion during Running after Anterior Cruciate Ligament Reconstruction, Am. J. Sports Med. 32 (2004) 975–983.

[30] S. Tashman, P. Kolowich, D. Collon, K. Anderson, W. Anderst, Dynamic Function of the ACL-reconstructed Knee during Running, Clin. Orthop. Relat. Res. Number. 454 (2006) 66–73.

[31] J.C. Waite, D.J. Beard, C.A.F. Dodd, D.W. Murray, H.S. Gill, In vivo kinematics of the ACL-deficient limb during running and cutting, Knee Surgery, Sport. Traumatol. Arthrosc. 13 (2005) 377–384.

[32] S.F. Scanlan, A.M.W. Chaudhari, C.O. Dyrby, T.P. Andriacchi, Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees, J. Biomech. 43 (2010) 1817–1822.

[33] T. Alkjar, E.B. Simonsen, S. Peter Magnusson, H. Aagaard, P. Dyhre-Poulsen, Differences in the movement pattern of a forward lunge in two types of anterior cruciate ligament deficient patients: Copers and non-copers, Clin. Biomech. 17 (2002) 586–593.

[34] H. Hart, K. Crossley, D. Ackland, S. Cowan, N. Collins, Effects of an unloader knee brace on knee-related symptoms and function in people with post-traumatic knee osteoarthritis after anterior cruciate ligament reconstruction, Knee. 23 (2016) 85–90.

[35] G. Harput, B. Ulusoy, H. Ozer, G. Baltaci, J. Richards, External supports improve knee performance in anterior cruciate ligament reconstructed individuals with higher kinesiophobia levels, Knee. 23 (2016) 807–812.

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